〒Design,Kinematics,and Control of a High-Speed 4-DOF Parallel Robot(4自由度高速パラレルロボットの設計,運動学.制御)〒

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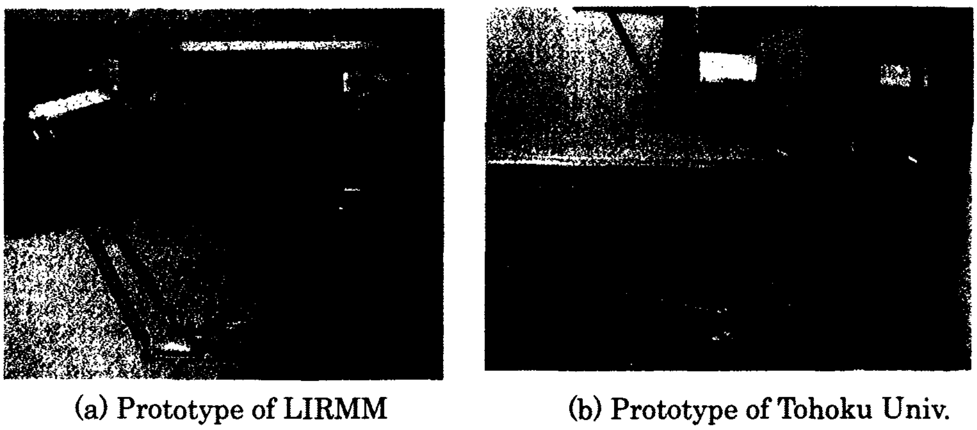
論文内容要旨

Chapter 1. Introduction

Many kinds of parallel robots have been studied enthusiastically for several decades. Especially 3- and 6-DOF parallel robots have been mainly suggested and developed. In some case, a DELTA robot can have 6-DOF in total with the addition of serially actuated 3-DOF. This kind of serial-parallel hybrid robot is not as efficient as a fully parallel robot. In contrast, Pierrot proposed a 6-DOF fully parallel robot HEXA that is the result of expanding of the DELTA mechanism.

However, the HEXA robot suffers from its high-price, small tilting angle, and complexity. There are a lot of applications in which 3-DOF is not enough and 6-DOF are too much. For example, 4-DOF (3-DOF for translation and 1-DOF for rotation) is necessary and enough for pick-and-place tasks. Nevertheless, only few attempts have so far been made to develop 4-DOF parallel robots. Pierrot proposed 4-DOF parallel mechanisms called H4 against such a background (Fig. 1 (a)). Pierrot's H4 robot has large workspace and high-speed acceleration along z-axis. However, a parallel robot that has larger workspace and good characteristics along x-y plain is eagerly required for industry application. For the reasons as cited above, this dissertation will discuss design, kinematics, and control of a new 4-DOF parallel robot (Fig. 1 (b)).



(a) Prototype of LIRMM　　(b) Prototype of Tohoku Univ.

Fig. 1 Prototype of the H4 robot

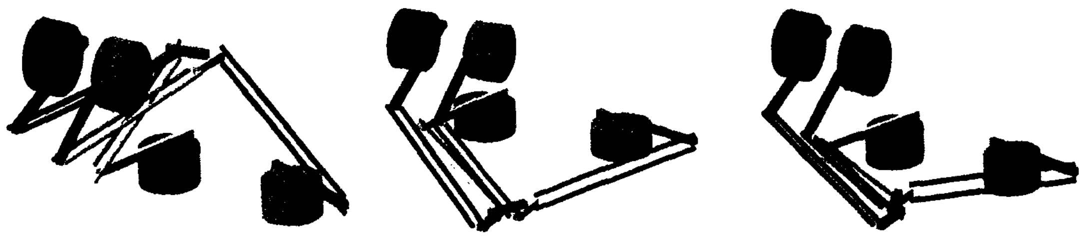
Chapter 2. Description of the H4 Robot

In this chapter, design of the 4-DOF parallel robot H4 is described. A design of a parallel robot, which could provide high performance in terms of speed and acceleration, is very important. In the case of fully parallel robot, the number of chains is equal to the number of degrees of freedom. One actuator will usually drive each chain. This kinematic structure allows parallel robots to be driven by actuators mounted at the base frame. Mounting the actuators at the base not only reduces the moving inertia of the motors, but also allows for lighter links. In addition, parallel robots can have high payload capacity, and high stiffness, because the load is distributed among several actuators.

To satisfy such characteristics as mentioned above, the structure, mobility, and a necessary condition for a symmetrical design of the H4 robot are also presented. Moreover, the manipulability ellipsoid and the manipulability measure are proposed as a quantitative measure of their manipulating ability in positioning and orienting the end-effector.

Chapter 3. System Configuration of the H4 Robot

In this chapter, the system configuration of the 4-DOF parallel robot H4 is described. The configuration of the H4 robot, i.e., arms, rods, travelling plate, and ball joints, are presented. Control system and the interface of the H4 robot are also introduced.



(a) (b) (c)

Fig.2. Solutions of forward kinematics

Chapter 4. Kinematics

This chapter will be devoted to the kinematics of the H4 robot which means studying geometrically the motion of the H4 robot links. Kinematics deals with the aspects of motion without regard to the forces and torques that cause it or result from the motion. Inverse kinematics is to find all possible sets of actuated joint variables and their corresponding time derivatives which will bring the travelling plate to the set of desired positions and orientations.

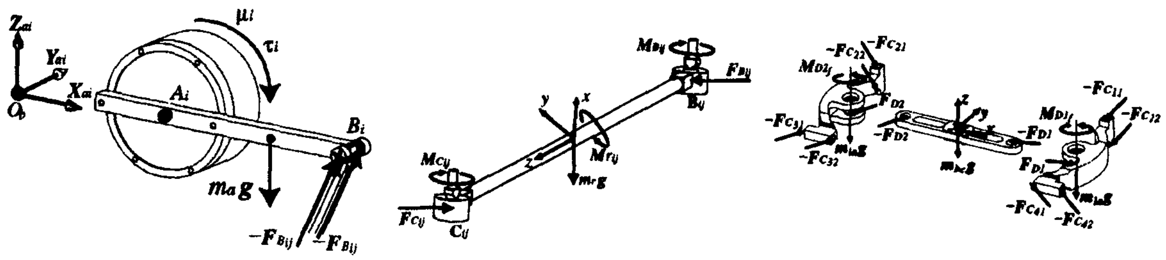
On the other hand, forward kinematics is to find all possible sets of travelling plate positions and orientations. Typically, as the number of kinematic chains increases, the forward kinematics becomes more difficult. It is well known that in the case of a 6-DOF conventional serial robot the forward kinematics is relatively simple, while the inverse kinematics is difficult. For the forward kinematics of the H4 robot the closed-form solutions are derived. It is shown that the solutions of the forward kinematics yield a 16th degree polynomial in a single variable

(Fig. 2). To express the positions and orientations of the H4 robot, an assignment of a coordinate frame is explained. And the workspace of the H4 robot is shown.

Chapter 5. Jacobian and Singularity Analysis

In this chapter, analytic singularity analysis of the H4 robot is addressed. Since a parallel robot consisted of several serial chains has complex singularities in the workspace, the determination of singular configurations is very important in design, trajectory planning, and control. The classical method to determine singular configurations is to find the determinant of the Jacobian matrix. However, the Jacobian matrix of a parallel robot is complex in general and it is not easy to find the determinant of the Jacobian matrix.

For deriving the screw-based Jacobian matrix and the analysis of the singularities of the H4 robot, the theory of the reciprocal screw is used. The reason is that the conventional Jacobian matrix is simply not valid. However, by using screw theory, configurations of singularities could be explained correctly. We focus on the singularity analysis of the H4 robot using analytical Jacobian matrix based on the theory of reciprocal screw and its deficiencies. Two types singularities named overmobility (forward singularity) and undermobility (inverse singularity) have been presented.



(a) arm (b) rod (c) travelling plate

Fig. 3. Dynamic model of the H4 robot

Chapter 6. Dynamics

In this chapter, dynamics of the H4 robot is addressed. In contrast to kinematics which deals with the geometry and time-dependent aspects of motion without considering the forces causing motion, dynamics based on kinematics includes the effect of the inertia forces. Dynamics of parallel robots is one of a very complicated subject. Typically, dynamics is described in terms of the time rate of change of a given travelling plate's trajectory in relation to the joint torque exerted by the actuators. The actuating torque would depend not only on a given trajectory but also on the mass properties of the arms, the rods, travelling plate, and external forces.

There are two types of dynamical analysis problems namely forward dynamics and inverse dynamics. Such dynamics are useful for computer simulation of parallel robots, the design of suitable control equations, and the evaluation of the kinematic design. For the real time control of the parallel robot, the computational efficiency of inverse dynamics is one of the important issues. As alternative methods for dynamics analysis, such as the Newton-Euler method, the

Lagrangian methods, and the principle of virtual work can be applied.

The detailed and simplified dynamic equation for the H4 robot will be derived using Newton-Euler method (Fig. 3). A simplified dynamic model is adopted to decrease the cost of computation. By using those methods to the control, the effect of the rod inertia with fast motion is discussed in the chapter 7.

Chapter 7. Performance Evaluation

In this chapter, the performance evaluation of the H4 robot is presented. Three different types of controls, i.e., PD control, PD with velocity feed-forward control, and dynamic control, are developed and tested for the H4 robot to explore the performance of each type as applied to this parallel robot. Each of these comes from three different broad categories of controls.

The first type of control is based upon the classical proportional-derivative (PD) control. To compensate the response delay, PD with velocity feed-forward control is used in the second control. The third type is a dynamic control which uses a model of the inverse dynamics of the H4 robot to estimate the actuation required for the H4 robot to achieve a desired trajectory. Since the dynamic control takes into account the nonlinear and coupled nature of the parallel robots, the trajectory tracking accuracy is expected to develop.

However, the difficulty to a dynamic control is that it requires a good model of the inverse dynamics and good estimates of the model parameters, making this control more complex and difficult to implement than the other control. In order to compare the simulation result with experimental result, a precise model of the H4 robot is constructed by ADAMS. Each type of control scheme developed for the H4 robot is briefly explained. The Adept motion is chosen as a benchmark test to evaluate its capability of fast motion.

In addition, the dynamic equation derived in Chapter 6 is validated using ADAMS. Finally, it is also proven that the effect of the light rod inertia is negligible in a very fast motion.

Chapter 8. Conclusion

In this dissertation, the design, kinematics, and control aspects of a novel 4-DOF parallel robot H4 were presented. The description, system configuration, kinematics, dynamics, singularity analysis, and control of the H4 robot were mainly discussed. The major results were summarized as given below.

The H4 robot provides three translational motions and one rotational motion of the travelling plate. The main advantages of the H4 robot are (1) all four actuators can be attached to the base directly, (2) it was constructed with cheaper ball joints as passive joints, and (3) high-speed motion is possible.

審査結果の要旨

パラレルロボットは、速度、精度、剛性などの点でシリアルロボットより優れ、産業用ロボットとしての実用化が期待されている。一方、産業用途では、ピックアンドプレース作業に代表されるように、並進3自由度とヨー軸周りの1回転があれば十分な作業が多く、このような作業に6自由度のパラレルロボットを用いるのは、2自由度分が無駄となり、コスト的に不利である。本論文は、このような用途への応用を目的に、新しい機構の4自由度パラレルロボット（以下、H4と呼ぶ）を開発し、その逆運動学、順運動学解法の提案、特異姿勢の解析、動力学計算法の提案、動力学を考慮した制御則の構築、性能検証を行ったもので、全編8章よりなる。

第1章は序論であり、本研究の背景および目的を述べている。

第2章では、設計、開発したパラレルロボットH4の仕様、設計コンセプト、機構について述べている。

第3章では、H4の制御システムについて述べている。

第4章では、H4の逆運動学解、順運動学解を導いている。パラレルロボットの順運動学解は直接求められる場合は少なく、収束計算で求める方法が一般的であるが、本章では、H4の順運動学解が16次多項式の解として得られることを示している。新しい機構のH4について、順運動学の直接解法が存在することを示したことは、意義が大きい。

第5章では、スクリュー理論を応用し、H4のヤコビ行列を導出するとともに、幾何学的に特異姿勢を解析する手法を提案している。ヤコビ行列の階数を計算して特異姿勢を見つける従来の方法では、すべての可能性のある位置、姿勢に対して階数を計算する必要があり、また、特異姿勢が見つかったとしても、なぜ特異姿勢になるのか、その幾何学的意味を見出すことが困難であった。本章の手法は、特異姿勢の幾何学的意味を明確に与えるため、有用性が高い。

第6章では、H4の動力学計算法を提案している。提案された手法は、パラレルロボットを開リンク機構に分解したり、ラグランジュの未定乗数を使用する必要がなく、直感的で理解しやすい。また、H4以外のパラレル機構にも適用可能で、発展性がある。

第7章では、市販の動力学シミュレータを用いたシミュレーションと実機で行った実験結果について、比較、考察している。ジョイント角のPD制御、PD制御にフィードフォワード項を加えた制御、簡易動力学モデルを用いた動的制御、詳細動力学モデルを用いた動的制御の各制御則に対してシミュレーションと実験を行い、それぞれの制御則の特徴、限界を明らかにしている。

第8章は結論である。

以上要するに本論文は、新しい4自由度パラレルロボットH4を開発し、運動学、動力学について論じ、特に順運動学の解法、幾何学的見地からの特異姿勢解析、および動力学解法について新規性のある提案を行ったもので、その成果は機械工学およびロボット工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。